Possible Infrared Counterparts to the Soft Gamma-Ray Repeater SGR 1806-20

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ABSTRACT

We report the discovery of possible infrared counterparts to SGR 1806-20. We use archival *Chandra* observations to determine the location of SGR 1806-20 to $< 1''$ accuracy. We then locate 2 infrared objects within this error circle in K-band (2.2μm) images of this field. Based on the X-ray absorption towards SGR 1806-20 and the extinction towards the nearby star cluster, we discuss the likelihood of association for the possible counterparts, and the implications for SGR 1806-20's physical properties and origins.

Subject headings: gamma rays: bursts — stars: neutron — supernova remnants — X-rays: stars

1. Introduction

The soft gamma-ray repeaters (SGRs) are unusual objects, even for the rarefied field of compact object astrophysics, with only 4 definitely identified over the last 30 years. As a class, they are defined by their repeated super-Eddington soft gamma-ray bursts (peak photon energy ~ 30 keV, versus ~ 300 keV for "classical" gamma-ray bursters), with occasional outbursts *greatly* exceeding the Eddington luminosity for a $\sim 1M_\odot$ object. During a giant outburst, SGR 0526-66 showed 8-second pulsations (Mazets et al. 1979), and SGR 1900+14 showed 5-second pulsations during a similar outburst some 20 years later (Hurley et al. 1999a). Both SGR 1900+14 and SGR 1806-20 show X-ray pulsations (5-s and 7.5-s, respectively) in quiescence (Kouveliotou et al. (1998); Hurley et al. (1999b)). Based on their spin periods and period derivatives, SGRs appear similar to the so-called Anomalous X-ray Pulsars (AXPs) (Stella et al. 1998). Currently, the most widely investigated model for both SGRs and AXPs is the so-called "magnetar" model, in which a highly-magnetized young

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neutron star has X-ray emission powered by the decay of its magnetic field, and the soft gamma-ray bursts are powered by magnetic realignment in the neutron star crust (Duncan & Thompson (1992); Thompson & Duncan (1993)). Other models have also been proposed (e.g. Marsden et al. (2001)).

One motivation for considering SGRs as young neutron stars has been their apparent association with young supernova remnants, particularly the association of SGR 1806-20 with the radio nebula G10.0-0.3 (Vasisht et al. (1993); Kulkarni & Frail (1993)). At one time, SGR 1806-20 was thought to be associated with a luminous blue variable (LBV) star which lies at the time-variable (in both flux and morphology) core of this nebula. However, the recent Inter-Planetary Network (IPN) localization of SGR 1806-20 provides a position inconsistent with that of the LBV star and radio core (Hurley et al. 1999c). Furthermore, (Gaensler et al. 2001) argue that G10.0-0.3 is not a supernova remnant at all; rather it may be powered by the tremendous wind of the LBV star (Hurley et al. 1999c). Infrared observations of the field of SGR 1806-20 reveal that the LBV star is not alone, but appears to be part of a cluster of embedded, hot, luminous stars (Fuchs et al. 1999), and the IPN position for SGR 1806-20 is consistent with membership in that cluster. Recently, Eikenberry et al. (2001) have used near-infrared photometry and spectroscopy to conclude that this cluster contains what may be the most luminous star in the Galaxy (the LBV star), at least one Wolf-Rayet star of type WCL, and at least two blue "hypergiants" of luminosity class Ia+. These properties make the cluster resemble a somewhat smaller and older version of the "super" star cluster R136 (Massey & Hunter 1998), making the potential association with SGR 1806-20 even more intriguing.

We report here X-ray observations of SGR 1806-20 with the *Chandra X-ray Observatory* (Weisskopf et al. 1996), as well as near-infrared observations of the field with the Cerro Tololo Inter-American Observatory (CTIO) 4-meter telescope and the Hartung-Boothroyd Observatory 0.65-m telescope. Using *Chandra* to localize SGR 1806-20 to an accuracy $< 1''$, we then can identify possible infrared (IR) counterparts to SGR 1806-20. In Section 2, we describe the observations and data analysis. In Section 3, we discuss the results and their implications for SGR 1806-20 and other soft gamma-ray repeaters, and in Section 4 we present our conclusions.

2. Observations & Analysis

2.1. *Chandra* Observations

We analyzed an archival *Chandra* observation of SGR 1806-20 taken on 24 July 2000 UT. The observation duration was 4900 seconds, with the aim point on the back-illuminated ACIS-S3 CCD chip. Because the time-resolution was 3.24-s (full-frame mode), sources as bright as SGR 1806-20 suffered from significant photon pileup in the core ($\sim 30-40\%$ here). This effect limits spectroscopic accuracy, and also prevents detailed analysis of the spatial profile near the (suppressed) image core, but does not greatly impair the source localization. We used the *CIAO 2.1.3* and *SHERPA 2.1.2* software packages for *Chandra* to perform the analyses of the data.

We present a section of the Chandra image of this field in Figure 1, revealing a single bright source near the expected position of SGR 1806-20. Within the limits imposed by pileup, the source appears to be unresolved (Gaussian $\sigma = 0.8$ pixels $= 0.4''$), and has a centroid of α_{2000} = 18h 08m 39.32s and $\delta_{2000} = -20^\circ\ 24'\ 39.8''$ based on the *Chandra* aspect solution. The uncertainty in this position is dominated by the systematic offsets in the *Chandra* aspect solution, which are typically $0.5-1.0''$. Kaplan et al. (2001) have used deeper *Chandra* observations of this field to identify several X-ray counterparts of nearby USNO-A2.0 stars, and based on them find a corrected position of α_{2000} = 18h 08m 39.32s and $\delta_{2000} = -20^\circ\ 24'\ 39.5''$, with uncertainties in each coordinate of $\pm 0.3''$, in good agreement with our position above. Thus, we adopt the more accurate position of Kaplan et al. (2001) from here on.

Despite the limitations imposed by the pulse pileup, we attempted crude spectral analyses on the *Chandra* observation. We extracted a background-subtracted spectrum for the point source and then modelled it as an absorbed power-law, obtaining a best-fit with $\chi^2_\nu = 0.88$ for 41 degrees of freedom. This produced an absorption estimate of $n_H = 4.5(\pm 1.0)\ \times 10^{22}$ cm^{-2} and a flux of $\sim 6 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 2-10 keV band – both in good agreement with the *BeppoSAX* observations of Mereghetti et al. (2000).

2.2. Infrared Observations

We obtained near-infrared images of the field of SGR 1806-20 using the Ohio State InfraRed Imaging Spectrograph (OSIRIS) intrument (Depoy et al. 1993) and f/14 tip-tilt secondary on the CTIO 4-meter telescope on 6 July 2001 UT. We note that no IPN bursts had been observed from SGR 1806-20 for 2 weeks prior to this date. We used the f/7 camera

of OSIRIS, providing a plate scale of $0.161''$ per pixel and an unvignetted field of view of $\sim 100''$ on a side. We observed the field in the J, H, and K bands (central wavelengths of 1.25μm, 1.65μm, and 2.2μm, respectively). For each band, we obtained 9 separate images in a 3×3 grid pattern offset by $\sim 10''$. The integration times for each image were 3.24, 3.24, and 10 seconds for J,H, and K bands respectively. We then subtracted dark frames from each image, divided the result by its own median, and then median-combined the resulting images into a normalized sky frame. We subtracted the dark frame and a scaled version of the sky frame from each of the 9 images, and divided the result by a dome flat image. We shifted each of the 9 frames to a common reference position and averaged them to give a final image in each band.

Due to the presence of variable thin clouds during the CTIO observations, we photometrically post-calibrated these images using observations of stars in the field of SGR 1806-20 and infrared standard stars on July 27, 2001 with the Hartung-Boothroyd Observatory 0.65-meter telescope and its infrared array camera (Houck & Colonno 2001). We took 7 images of the field of SGR 1806-20 in each band, with offsets of $\sim 15''$ between images. We then processed the images in each band as described for the CTIO data above. We repeated this procedure on sets of 7 images of the UKIRT standard FS26 in each band. We extracted the flux in ADU/s from each processed image of FS26 individually, using the average as the best estimate of the flux, and the standard deviation as the 1σ uncertainty. We then used the known magnitudes of this star to calibrate similarly-derived flux measurements and uncertainties for several bright stars in the field of SGR 1806-20. We used a photometric airmass solution derived from measurements of stars observed for another program over a range of airmasses throughout the night.

For astrometric calibration, we had several USNO-A2.0 stars present in the J-band image. We chose 8 of the brightest stars (Figure 2a), and peformed a least-squares linear fit to determine the best astrometric solution. We found an RMS of $< 0.15''$ in each coordinate, including the USNO-A2.0 relative uncertainties which can be as large as $0.25''$. We then used the centroids of several IR-bright stars to transfer this coordinate system onto the H- and K-band images (Figure 2b,c). We found this approach to provide superior results to simply applying an astrometric solution to the USNO stars visible in the H- and K-band images – reddened stars greatly increase crowding in these images and thus increase contamination of the centroids of the USNO stars. The transfer of coordinates produced an additional RMS uncertainty of $< 0.08''$ in each coordinate for the H- and K-band images. Since the X-ray position for SGR 1806-20 of Kaplan et al. (2001) also derives from USNO-A2.0 stars, the two solutions should be directly comparable. Thus, the 90% positional uncertainty we can provide for the location of SGR 1806-20 on the infrared images is $0.7''$. We present J-, H-, and K-band images of the region near SGR 1806-20 in Figure 3, along with the 90%

positional error circle. We present photometry of the labelled stars in Table 1.

3. Discussion

3.1. The Distance to SGR 1806-20

As noted above, SGR 1806-20 lies in the direction of an unusual embedded cluster of massive, luminous young stars (Fuchs et al. (1999); Eikenberry et al. (2001)), with a distance of 14.5 ± 1.4 kpc and a reddening of $A_V = 29 \pm 2$ mag (Corbel et al. (1997); Eikenberry et al. (2001)). The LBV star is perhaps the most luminous star known at $L > 6 \times 10^6\ L_\odot$, and the Wolf-Rayet and blue hypergiant stars are also certain to be very massive (Eikenberry et al. 2001). The fact that stars D and E in Figure 3 have $J - K = 5.0$ mag indicates that they are members of this cluster ($E_{J-K} = 5.0$ mag for $A_V = 29$ mag), and thus that SGR 1806-20 lies within the radial extent of the cluster on the sky. Furthermore, the X-ray absorption towards SGR 1806-20 is $\sim 5 - 6 \times 10^{22}$ cm^{-2} (see above, and Mereghetti et al. (2000)), which is consistent with the extinction towards the cluster. Thus, it seems likely that SGR 1806-20 is also a member of this massive star cluster at a distance of 14.5 ± 1.4 kpc. It is very interesting to note that the soft gamma-ray repeater SGR 1900+14 is also very near to a cluster of embedded luminous stars (Vrba et al. 2000). The projected distance from the center of this cluster to the location of SGR 1900+14 is < 1 pc.

3.2. The IR Counterparts

The IR colors (and upper limits) of the two candidate counterparts to SGR 1806-20 are consistent with both of them being stellar members of the star cluster ($J - K = 5.0$ mag, $H - K = 2.0$ mag). Note that the brighter star just outside the error circle ("C" in Figure 3) appears to be a foreground star ($J - K = 3$ mag), confirming that it is not a likely counterpart to the SGR. However, as can been seen in Figure 3, the field of SGR 1806-20 is highly crowded in the IR by both foreground/background objects and cluster members, and the simple fact that two stars lie within the 90% confidence error circle and another just outside it shows that the probability of a chance coincidence of unrelated IR objects is high. Thus, we cannot conclude definitely that *either* of the possible counterparts is actually related to SGR 1806-20. Monitoring for variability may resolve this issue in the future.

If both candidates are in fact members of the cluster, we can estimate their absolute magnitudes to be $M_K = -2.3$ mag (A) and $M_K = -0.4$ mag (B). For Star A, this is consistent with stars of luminosity matching a B1V or K3III star, and is inconsistent with any stars

of luminosity class I. After correcting for the $H - K = 2$ mag differential extinction toward the cluster, the intrinsic color of $(H-K)_{intrins} = 0.8 \pm 1.2$ mag is essentially consistent with all stellar spectra earlier than late M, and does not significantly constrain the classification. For Star B, the absolute magnitude is consistent with stars of luminosity matching a B8V star, and is inconsistent with any stars of luminosity class III or higher. It is important to note that no observations have yet probed the distribution of stars in the cluster with masses below that of late B main sequence stars. Thus, it is possible that there are even further stars within the error circle at significantly lower mass/luminosity, unless the cluster mass distribution shows a sharp lower cutoff.

3.3. The SGR Progenitor Star

One particularly intriguing aspect of the association between SGR 1806-20 and the star cluster is that a neutron star progenitor went supernova *before* the stars currently observed in the cluster. Since more massive stars evolve to the supernova stage more rapidly, *if* the progenitor of SGR 1806-20 formed at the same time as the currently observed massive stars, its mass must have been greater. However, the mass estimate for the LBV is $> 200 M_{\odot}$ (Eikenberry et al. 2001), and several of the other stars are likely to have masses in the range of $\sim 50 - 100 M_{\odot}$ (Eikenberry et al. 2001). While recent theories have predicted that very massive stars may produce neutron star remnants due to the effect of envelope loss via dense stellar winds, the upper limit on their masses is $\sim 80 M_{\odot}$, with higher mass stars producing massive black hole remnants. Thus, it seems unlikely that the SGR 1806-20 progenitor formed at the same time as the currently observed massive stars in the cluster.

Alternately, SGR 1806-20 may have formed prior to these stars – in fact, Kaplan et al. (2001) suggest that the supernova event that produced SGR 1806-20 may have triggered the star formation activity that produced the massive stars in the cluster. However, the massive stars we observe in the cluster are evolved, with ages of $\sim 10^6$ yr to reach the LBV and Wolf-Rayet stages of their lives. If the SGR 1806-20 supernova event led to the birth of these stars, then SGR 1806-20 is much older than the $\sim 10^3 - 10^4$ yr typically considered for magnetars. Alternately, SGR 1806-20 may simply be taken as evidence for prior massive star formation at this location. While at least one supernova occurred here, perhaps it was not the first, and an earlier supernova event triggered the formation of the currently observed massive stars.

4. Conclusions

We have presented X-ray and infrared observations of the field of SGR 1806-20, determining the location of the X-ray counterpart in the IR image to an accuracy of $0.7''$ (90% confidence). We find two potential counterparts in this small error circle, and the crowding in this field makes it difficult to ascertain which if either of these stars is a true counterpart to SGR 1806-20. The X-ray absorption towards SGR 1806-20 matches the infrared extinction of cluster members, indicating that the SGR 1806-20 is at the same distance as the cluster (14.5 ± 1.4 kpc), and the IR observations reveal that it lies within the radial extent of the cluster on the sky. The presence of a neutron star in a cluster containing extremely massive evolved stars indicates either that the neutron star progenitor was more massive (which seems unphysical) or that these stars are the result of the most recent of multiple star formation epochs at this location.

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Table 1. Photometry of Stars

Star	J-band (1.25μm)	H-band (1.65μm)	K-band (2.2μm)
A	> 21	19.5 ± 1.0	16.7 ± 0.2
B	> 21	$> xx$	18.6 ± 1.0
C	19.2 ± 0.2	17.2 ± 0.2	16.1 ± 0.2
D	18.8 ± 0.2	15.5 ± 0.2	13.87 ± 0.15
E	17.1 ± 0.2	14.00 ± 0.15	12.00 ± 0.11

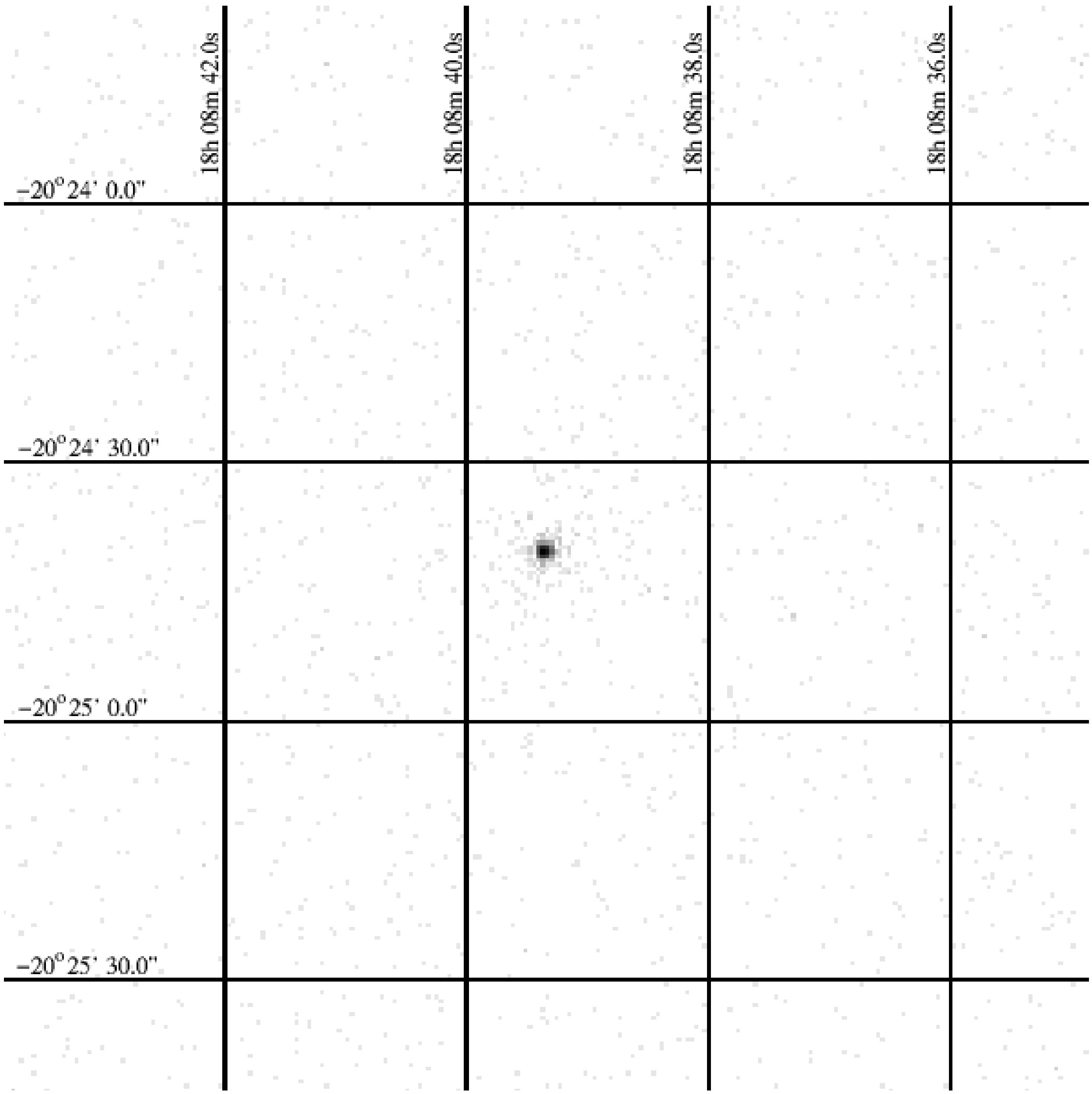

Fig. 1.— *Chandra ACIS image of the field of SGR 1806-20. The field of view is approximately* $2'$ *on a side. The image intensity is scaled logarithmically. Coordinates are J2000.*

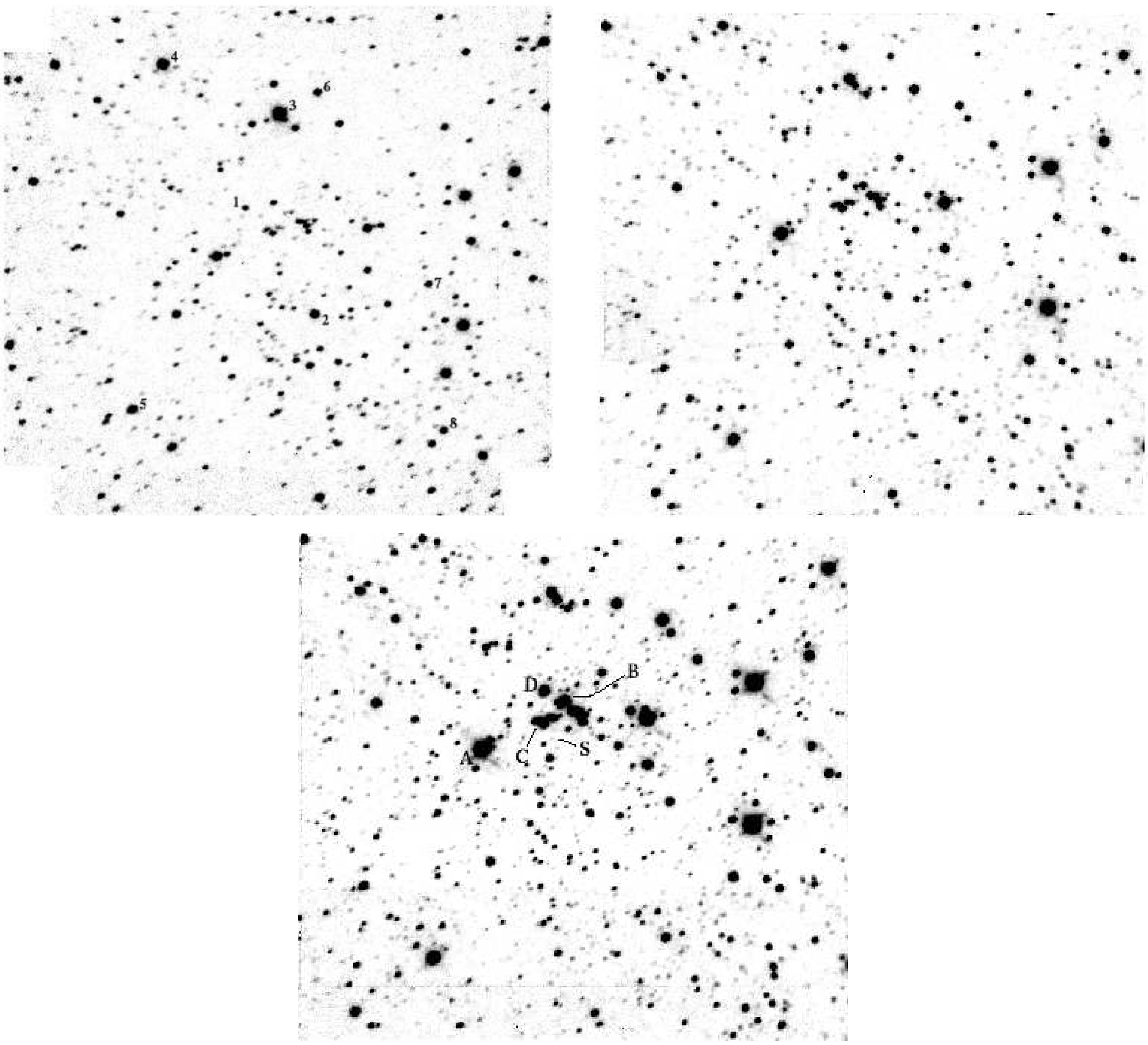

Fig. 2.— *Near-infrared images of the field of SGR 1806-20 in the J-band (top left), H-band (top right), and K-band (bottom). The field of view is approximately* $100''$ *on a side, with North up and East to the left. In the J-band image, numbers indicate the 8 USNO-A2.0 stars used for astrometric calibration of the images. In the K-band image, letters indicate the position of SGR 1806-20 (S), as well as the 4 brightest stars in the nearby cluster (see Eikenberry et al. (2001) for details): the luminous star LBV 1806-20 (A), a Wolf-Rayet WCL star (B), two blue hypergiants of luminosity class Ia+ (C,D).*

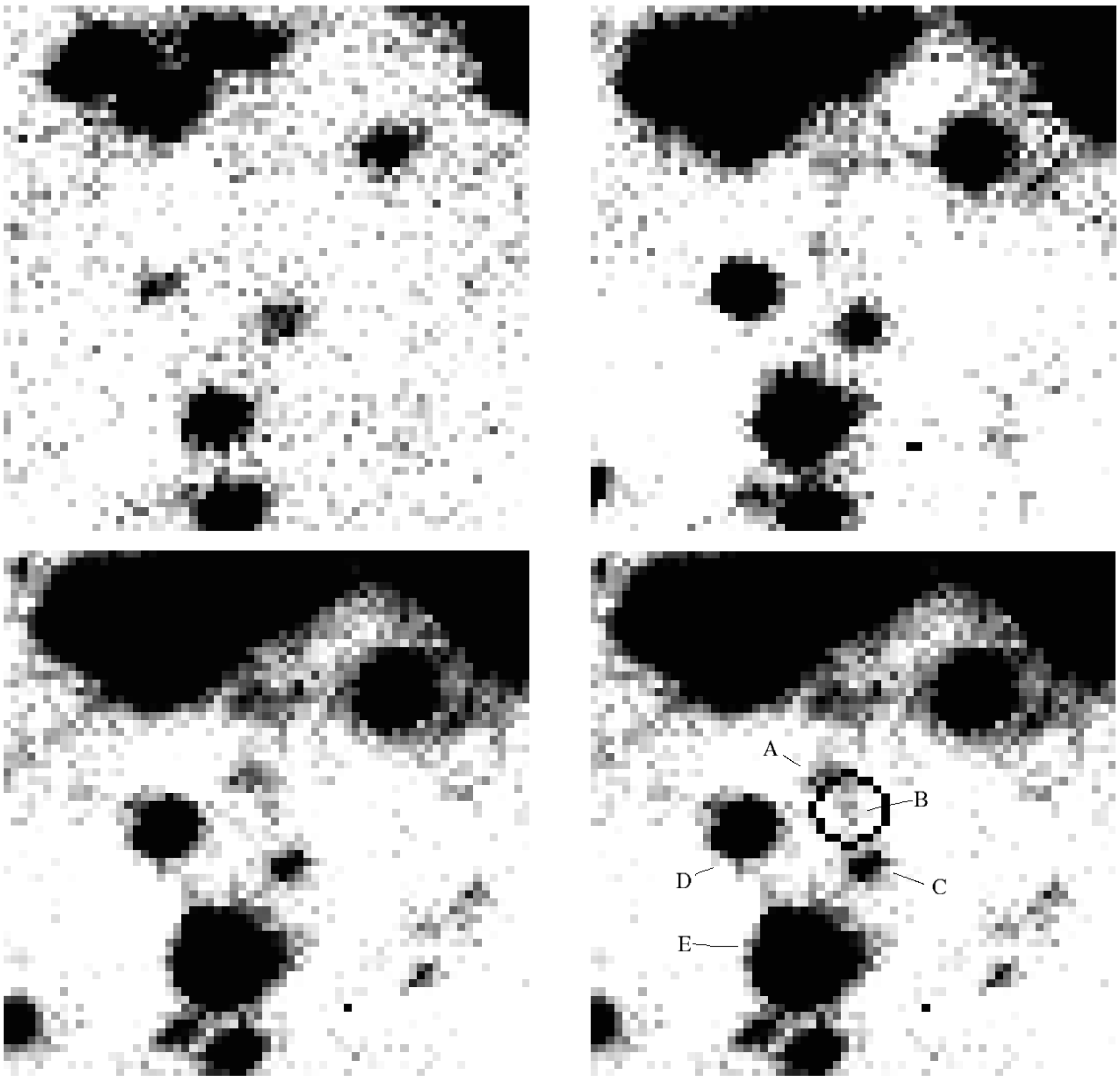

Fig. 3.— *Close-up of the region near SGR 1806-20 in the J-band (top left), H-band (top right), and K-band (bottom left). The bottom right image is a copy of the bottom left with the* $0.7''$*-radius error circle for SGR 1806-20 superimposed, as well labels for the stars listed in Table 1. The images are approximately* $10''$ *on a side.*